

# STELLAR WINDS FROM MASSIVE STARS

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**Abstract** We review the various techniques through which wind properties of massive stars – O stars, AB supergiants, Luminous Blue Variables (LBVs), Wolf-Rayet (WR) stars and cool supergiants – are derived. The wind momentum-luminosity relation (e.g. Kudritzki et al. 1999) provides a method of predicting mass-loss rates of O stars and blue supergiants which is superior to previous parameterizations. Assuming the theoretical  $Z^{0.5}$  metallicity dependence, Magellanic Cloud O star mass-loss rates are typically matched to within a factor of two for various calibrations. Stellar winds from LBVs are typically denser and slower than equivalent B supergiants, with exceptional mass-loss rates during giant eruptions  $\dot{M} = 10^{-3} \dots 10^{-1} M_{\odot} \text{ yr}^{-1}$  (Drissen et al. 2001). Recent mass-loss rates for Galactic WR stars indicate a downward revision of 2–4 relative to previous calibrations due to clumping (e.g. Schmutz 1997), although evidence for a metallicity dependence remains inconclusive (Crowther 2000). Mass-loss properties of luminous ( $\geq 10^5 L_{\odot}$ ) yellow and red supergiants from alternative techniques remain highly contradictory. Recent Galactic and LMC results for RSG reveal a large scatter such that typical mass-loss rates lie in the range  $10^{-6} \dots 10^{-4} M_{\odot} \text{ yr}^{-1}$ , with a few cases exhibiting  $\sim 10^{-3} M_{\odot} \text{ yr}^{-1}$ .

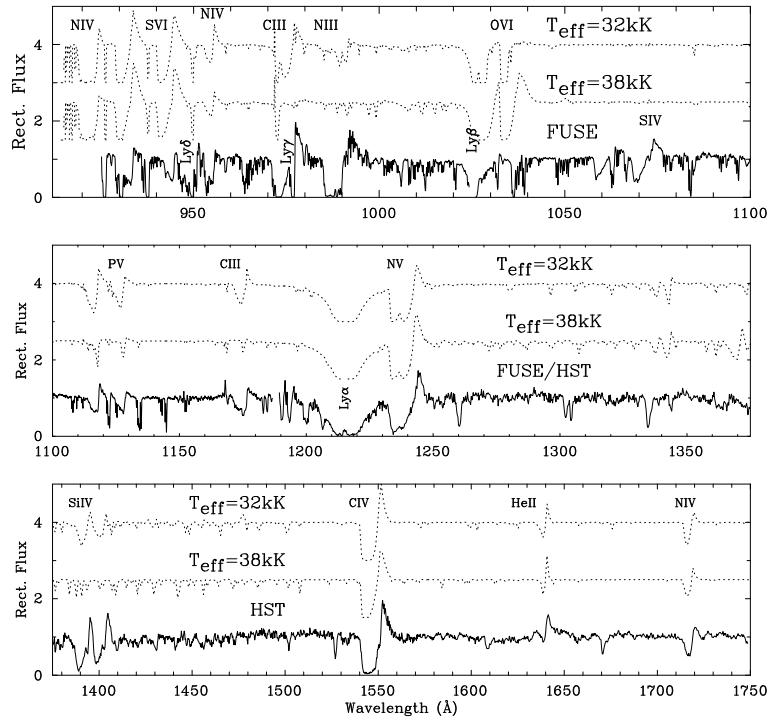
## 1. INTRODUCTION

Winds are ubiquitous in massive stars, although the physical processes involved depend upon the location of the star within the H-R diagram. Mass-loss crucially affects the evolution and fate of a massive star (Meynet et al. 1994), while the momentum and energy expelled contribute to the dynamics and energetics of the ISM. The interested reader is referred to Lamers & Cassinelli (1999) for the topic of stellar winds in general, or Kudritzki & Puls (2000) for a detailed discussion of mass-loss from OB stars. This review will cover the broad topics of

mass-loss from early-type (OBA, Wolf-Rayet, Luminous Blue Variable) and late-type (yellow/red supergiants) stars. Theoretical predictions for hot star winds follow line-driven radiation pressure (Castor et al. 1975; Pauldrach et al. 1986). Pulsations are thought to initiate the winds of cool supergiants, together with other mechanisms (e.g. Alfvén waves). Radiation pressure on dust grains helps to maintain outflows in their cool, outer envelopes (Wickramasinghe et al. 1966).

## 2. HOT STAR WIND DIAGNOSTICS

Global wind properties can be characterized by mass-loss and wind velocity. In hot stars, the former depends on application of varying complexity of theoretical interpretation, while the latter can fortunately be directly measured with minimal interpretation.



*Figure 1* Comparison between HST UV and FUSE far-UV spectra of Sk 80 (O7 Iaf) with synthetic spectra (including shocks) at  $T_{\text{eff}} = 37,500\text{K}$  and  $32,000\text{K}$ , illustrating the improved agreement for the latter value (Fullerton et al. 2000).

## 2.1. UV AND FAR-UV SPECTROSCOPY

Ultraviolet P Cygni profiles, ubiquitous in O-type stars (Walborn et al. 1985) provide a direct indication of stellar winds. Such metal resonance lines are generally analysed via the Sobolev with exact integration (SEI) method (Lamers et al. 1987; Haser et al. 1998). Mass-loss determinations require knowledge of elemental abundances, the degree of ionization of the ion producing the line, and an assumed form of the velocity law that is predicted by radiation driven winds. In practice, accurate wind velocities can be readily obtained from saturated UV P Cygni profiles (Groenewegen et al. 1989; Prinja et al. 1990), while unsaturated P Cygni profiles provide a better means of determining mass-loss rates, albeit still subject to ionization results from non-LTE atmospheric models. Such models are subject to uncertain contributions of ionizing radiation from shocks in the stellar outflow. In view of these difficulties, Lamers et al. (1999) have combined column densities from unsaturated UV P Cygni profiles with independently determined mass-loss rates (from radio or  $H\alpha$ , see below) to derive empirical ionization fractions.

The Far-Ultraviolet Spectroscopic Explorer (FUSE) offers the possibility of determining mass-loss rates solely from UV data alone, since the far-UV significantly increases the number of stellar wind diagnostics, including C III, N III-IV, O VI, Si IV-VI and P V. The additional ionization information provided by FUSE permits stellar temperature determinations. Fullerton et al. derived  $T_{\text{eff}}=32\text{--}33\text{kK}$  for two Magellanic Cloud O7 supergiants from UV wind metal diagnostics, in contrast to  $T_{\text{eff}}=38\text{kK}$  from the usual optical helium plane-parallel hydrostatic methods (see Fig. 1). Although previously derived mass-loss rates were confirmed, lower bolometric corrections implied reduced stellar luminosities, with consequences for current mass-loss calibrations.

## 2.2. OPTICAL AND NEAR-IR SPECTROSCOPY

Although  $H\alpha$  has long been recognized as the prime source of mass-loss information in early-type stars, accurate determinations rely upon a complex treatment of the lines and continua, i.e. non-LTE, spherically extended models which treat the sub- and supersonic atmospheric structure. Use of such codes also provide surface temperatures and gravity in OB stars via optical photospheric lines (e.g. He I-II in O stars). Problems with using fits to  $H\alpha$  to derive mass-loss rates include blending with He II  $\lambda 6560$  in O stars, together with nebular contamination from H II regions (e.g. NGC346; Walborn et al. 1995) and broadening of the

central emission component by stellar rotation. In A supergiants,  $H\alpha$  behaves as a scattering line, with a characteristic P Cygni profile, so they have the advantage over other hot stars that wind velocities and mass-loss rates may be simultaneously determined in external galaxies without the need for UV spectroscopy.

Although moderate to high spectral resolution observations of OB stars are rare at near-IR wavelengths (e.g. Fullerton & Najarro 1998), analogous lines to optical wind (and photospheric) diagnostics are available (Bohannon & Crowther 1999). This provides the prospect of the determination of mass-loss properties for hot stars obscured at optical wavelengths via IR diagnostics (Najarro et al. 1994).

### 2.3. IR–RADIO CONTINUA

Winds in hot stars can be readily observed at IR-mm-radio wavelengths via the free-free (Bremsstrahlung) ‘thermal’ excess caused by the stellar wind, under the assumption of homogeneity and spherical symmetry. Mass-loss rates can be determined via application of relatively simple analytical relations (Wright & Barlow 1975; Panagia & Felli 1975). Barlow & Cohen (1977) have used IR excess fluxes to determine mass-loss rates for a large sample of Galactic OBA supergiants, which generally compare favourably with recent  $H\alpha$  results for A and B supergiants (Kudritzki et al. 1999). Unfortunately, OB stars with relatively weak winds do not show a strong IR excess or radio flux, so mass-loss results have solely been for nearby hot stars with dense winds (Bieging et al. 1989; Drake & Linsky 1989). Observations at multiple frequencies are necessary to ensure against non-thermal (synchrotron) radio emission from colliding winds (e.g. Chapman et al. 1999).  $H\alpha$  and radio continuum mass-loss rates agree reasonably well (Lamers & Leitherer 1993) despite sampling quite different parts of the stellar wind –  $\sim 1.5$  stellar radii for  $H\alpha$  and  $\sim 1000$  stellar radii for the radio photosphere – placing constraints on relative clumping factors in these regions.

## 3. RESULTS FOR OBA STARS - ROLE OF METALLICITY?

Although the techniques used to study hot, massive stars are similar, we first discuss ‘normal’ early-type stars, and leave ‘exotica’ until subsequent sections. The mass-loss rate of a star is a fundamental ingredient in evolutionary models. Unfortunately, radiatively driven wind theory in its current form (Puls et al. 1996; Vink et al. 2000) is unable to reproduce the observed mass-loss properties for hot luminous stars sufficiently accurately (see below). Nevertheless, since their winds are driven

by photon momentum transfer through metal line absorption, the stellar momenta and wind velocities are expected to be functions of stellar metallicity,  $Z$ , such that mass-loss rates scale with  $Z^{0.5}$  for O stars and early B stars,  $Z^{0.8}$  for mid-B supergiants, and  $Z^{1.7}$  for A supergiants (Kudritzki & Puls 2000).

### 3.1. TERMINAL WIND VELOCITIES

Large compilations of wind velocities,  $v_\infty$ , of O-stars and AB supergiants have been made by Prinja et al. (1990) and Lamers et al. (1995), revealing a spectral type and luminosity class dependence. Lamers et al. highlighted the so-called ‘bi-stability’ jump in wind properties around B1.5 ( $\sim 21,000$ ), above which  $v_\infty \simeq 2.65v_{\text{esc}}$  (escape velocity), and  $v_\infty \simeq 1.4v_{\text{esc}}$  below, resulting from the change in ionization of the elements contributing to the line force (Vink et al. 1999). Wind velocities of LMC O stars differ little from Galactic counterparts (Garmany & Conti 1985), while a more prominent effect is observed in the SMC, particularly amongst early O stars (Walborn et al. 1995; Prinja & Crowther 1998).

*Table 1* Coefficients for wind momentum luminosity relationship of Galactic O-stars and AB supergiants (Kudritzki & Puls 2000)

<i>Sp Type</i>	<i>log D<sub>0</sub></i>	<i>x</i>
O dwarf/giant	19.87±1.21	1.57±0.21
O supergiant	20.69±1.04	1.51±0.18
B0–1 supergiant	21.24±1.38	1.34±0.25
B1.5–3 supergiant	17.07±1.05	1.95±0.20
A0–3 supergiant	14.22±2.41	2.64±0.47

### 3.2. MASS-LOSS RATES

Observationally, estimates of mass-loss rates from  $H\alpha$ , UV wind lines or radio fluxes have been available for the past 20 years, although is only recently that a reasonable degree of consistency has been reached between these different approaches via theoretical improvements. Puls et al. (1996) and Kudritzki et al. (1999) identified that O-stars and AB supergiants obey a wind momentum-luminosity relationship, as follows

$$\log \dot{M} v_\infty (R/R_\odot)^{0.5} = \log D_0 + x \log(L/L_\odot)$$

Stars of different spectral types have differing  $D_0$  and  $x$  values, listed in Table 1, because of the change of lines driving the stellar wind with  $T_{\text{eff}}$ .

Hot stars in the Magellanic Clouds provide us with the means to compare emirical mass-loss properties with predictions at lower  $Z$  (e.g. Garmany & Conti 1985). This has proved to be difficult given (i) the inability to measure radio fluxes for extra-galactic hot stars; (ii) the need to combine high quality UV and optical spectroscopy with sophisticated model techniques; (iii) the limited metallicity range spanned,  $0.15\text{--}1Z_{\odot}$ . Although the number of stars analysed in detail for the Magellanic Clouds remains small (Puls et al. 1996), the mass-loss rates of LMC and SMC O stars tend to be lower than Galactic counterparts. As an example, let us consider Sk 80 (O7 Iaf+) in the SMC giant H II region NGC 346 which has a metallicity of  $0.2Z_{\odot}$  (Haser et al. 1998; Peimbert et al. 2000). From the wind momentum-luminosity relationship we would expect an equivalent Galactic supergiant to have a mass loss rate four times higher than its observed value (Puls et al. 1996), suggesting a higher exponent of  $Z^{0.8}$  in this case.

*Table 2* Comparison ( $\dot{M}(T_{\text{eff}}, L)/\dot{M}_{\text{obs}}$ ;  $\sigma$  in parenthesis) between predicted OBA mass-loss rates from various parameterizations with empirical data from Puls et al. (1996) and Kudritzki et al. (1999). Parameterizations are de Jager et al. 1988; Lamers & Cassinelli 1996; Vanbeveren et al. 1998; Kudritzki & Puls (2000); Vink et al. (2000) or Achmad et al. (1997) for A supergiants. Except for Lamers & Cassinelli, no metallicity dependence is accounted for, so we here assume a metallicity dependence of  $Z^{0.5}$  for O stars, with  $0.4Z_{\odot}$  for the LMC,  $0.15Z_{\odot}$  for the SMC.

<i>Spect.</i> <i>type (#)</i>	<i>Galaxy</i>	<i>de Jager</i> <i>et al.</i>	<i>Lamers &amp;</i> <i>Cassinelli</i>	<i>Vanbeveren</i> <i>et al.</i>	<i>Kudritzki</i> <i>&amp; Puls</i>	<i>Vink</i> <i>et al.</i>
O (23)	Gal	0.9 (0.7)	1.1 (0.6)	0.9 (0.7)	1.3 (0.8)	1.8 (1.3)
O (6)	LMC	0.5 (0.5)	1.3 (0.7)	0.5 (0.3)	0.7 (0.3)	1.3 (0.4)
O (5)	SMC	1.3 (0.9)	2.5 (1.5)	1.3 (0.9)	2.3 (1.3)	6.5 (7.9)
B (14)	Gal	6.8 (4.6)	11.3 (7.7)		1.0 (0.3)	38.8 (29.4)
A (4)	Gal	5.0 (1.6)	3.7 (1.9)		1.0 (0.3)	2.0 (1.0)

Evolutionary calculations require  $\dot{M}(T_{\text{eff}}, L)$  parameterizations based on empirical data. Up until recently, the only compilation covering hot, luminous stars was that of de Jager et al. (1988). In an attempt to update the mass-loss calibration for evolutionary calculations, Vanbeveren

et al. (1998) provided an updated relationship for Galactic OB stars, while Lamers & Cassinelli (1996) additionally considered LMC/SMC O stars. Most recently, Achmad et al. (1997) and Vink et al. (2000) have provided a set of predictions from current radiative driven winds for A, F and G supergiants and OB stars, respectively. How do these different parameterizations compare with observed mass-loss rates?

We have taken empirical data,  $\dot{M}_{\text{obs}}$ , from Puls et al. (1996) for O stars and Kudritzki et al. (1999) for AB supergiants. In Table 2 we compare the mean ratio  $\dot{M}(T_{\text{eff}}, L)/\dot{M}_{\text{obs}}$  for each calibration. Perhaps surprisingly, de Jager et al. (1988) fares as well as the recent Lamers & Cassinelli or Vanbeveren et al. (1998) parameterizations for O stars. In contrast with previous theoretical results, Vink et al. (2000) predicts sufficiently strong winds, albeit a factor of 2 too *strong* for Galactic O stars. Overall, the mass-loss rates of AB supergiants are typically overestimated (by 5–10) with the exception of Kudritzki et al. (1999) and Achmad et al. (1997). Predictions by Vink et al. (2000) show the poorest agreement for mid-B supergiants.

Overall, solely the wind momentum-luminosity prescription provides excellent agreement with all OBA observations. One note of caution is warranted, since the  $T_{\text{eff}}$ -calibration for O stars, and hence the luminosity scale, relies almost universally on results from plane-parallel studies which neglect stellar winds (recall Sect 2.1).

### 3.3. ROTATION

O star rotational velocities ( $v \sin i$ ) are typically  $100 \text{ km s}^{-1}$  (Howarth et al. 1997), with important consequences for their evolution (Meynet & Maeder 2000). Friend & Abbott (1986) first considered the effect of centrifugal acceleration on hot star winds, extended by Bjorkman & Cassinelli (1993) to allow for the azimuthal dependence, who found that  $\dot{M}$  increases (and  $v_{\infty}$  decreases) towards the equator, leading to an oblate ‘wind-compressed disk’.

Subsequently, Owocki et al. (1996) established that quite different predictions may result, by additionally allowing for non-radial components of the line force, and the increased polar radiation flux via gravity darkening (von Zeipel 1924). Due to a reduced escape velocity, the equatorial velocity law is slower than at the pole, inhibiting the equatorial disk and the original scaling of mass-loss can be reversed, such that a prolate geometry results. As an example, a mid-B dwarf rotating at 85% of its critical velocity was found by Petrenz & Puls (2000) to have a strongly prolate structure ( $\rho_{\text{pole}}/\rho_{\text{eq}} \leq 15$ ) with a polar/equatorial terminal velocity of  $1030/730 \text{ km s}^{-1}$ . The global mass-loss rate was not

found to deviate from its 1D value by greater than 10–20%, except for supergiants close to the Eddington limit.

### 3.4. STRUCTURE

Observationally, evidence for structure in O stars winds has taken various forms, including absorption variability observed from optical (Fullerton et al. 1996) and UV (Prinja 1992) spectroscopic intensive monitoring, and the presence of soft X-ray emission (Chlebowski et al. 1989), attributed to shocks in their winds (Lucy & White 1980). This view has recently been questioned by Chandra observations of  $\zeta$  Ori (Waldron & Cassinelli 2000) which reveal that the X-ray emitting gas is exceptionally dense, with no evidence for expansion.

Theoretical studies of hot star winds reveal that line driven acceleration is subject to a strong instability, causing a variable and structured winds (Owocki et al. 1988; Feldmeier 1995). Since the region where  $H\alpha$  forms in OB stars ( $\leq 1.5R_*$ ) is not anticipated to be heavily structured, mass-loss determinations may not be greatly affected by clumping/structure. Recent extensive monitoring of HD 152408 (WN9ha or O8Iafpe) by Prinja et al. (2000) indicate variations of  $\pm 10\%$  in global mass-loss rate, although with a time averaged  $H\alpha$  profile that is remarkably stable over several years.

## 4. LUMINOUS BLUE VARIABLES

The stellar wind properties of LBVs are poorly constrained, although it is apparent that their winds are generally slower and denser than OBA supergiants (Crowther 1997), with little variation in mass-loss during their ‘normal’ irregular excursions across the H-R diagram (Leitherer 1997). To illustrate this, let us consider P Cygni, whose parameters have been determined by Najarro et al. (1997). Compared to normal B1.5 supergiants ( $780 \text{ km s}^{-1}$ ; Lamers et al. 1995), P Cyg has a very slow wind ( $185 \text{ km s}^{-1}$ ) and a mass-loss rate which exceeds the Galactic wind momentum relation (Sect. 2) by a factor of 15. Recall that from Petrenz & Puls (2000), non-rotating models of supergiants close to the Eddington limit may overestimate global mass-loss rates by a factor of  $\sim 2$ , so that differences may be somewhat less severe. There are numerous examples of extreme supergiants which are not LBVs yet show remarkably high mass-loss rates and low wind velocities (e.g. Hillier et al. 1998).

In the case of giant LBV eruptions, information is very scarce and up until recently solely reliant on the 1840’s  $\eta$  Car eruption causing the formation of the Homunculus, in which  $\sim 3 M_\odot$  was ejected over  $\sim 30$  years (Davidson & Humphreys 1997), corresponding to  $0.1 M_\odot$



$\text{yr}^{-1}$ . Within the past few years, two extra-galactic LBVs have had sudden giant eruptions, HD 5980 in the SMC (Barba et al. 1995) and V1 in NGC 2363 (Drissen et al. 1997). These eruptions, in stars at low metallicity environments, appear to be quite different from that of  $\eta$  Car during its eruption, since peak mass-loss rates of each are  $\sim 10^{-3} M_{\odot} \text{yr}^{-1}$  (Drissen et al. 2001), equivalent to the current mass-loss for  $\eta$  Car (Hillier et al. 2000).

## 5. WOLF-RAYET STARS

The diagnostics of mass-loss for Wolf-Rayet stars mimic O stars except that their stronger winds mean that UV/optical wind diagnostics are not restricted to resonance lines or  $\text{H}\alpha$ . Wind velocities can be accurately determined either from the usual UV P Cygni profiles (Prinja et al. 1990), or from optical/IR He I P Cygni profiles (Eenens & Williams 1994). Radio and mm fluxes have been used to determine mass-loss rates of Galactic WR stars (Leitherer et al. 1997), while recent theoretical progress (Schmutz 1997; Hillier & Miller 1998) now permits detailed non-LTE analysis of UV and optical observations. WR winds are typically spherical (Harries et al. 1998), but clumped (Lepine et al. 2000). Spectroscopic tools make use of electron scattering wings in WR winds to estimate clumping factors since their strength depends linearly on density, versus the square of density for the underlying recombination line (Hillier 1991). Typical volume filling factors are 5–10%, such that mass-loss rates in a clumpy medium are 3–4 times lower than those from homogeneous models (e.g. Hillier & Miller 1999).

Although great progress has been made in recent years, detailed analysis requires labour intensive use of complex models, so the sample of stars studied in detail remains small. Recently, Nugis & Lamers (2000) combined empirical IR-radio observations with analytical models accounting for clumping to estimate mass-loss rates as a function of luminosity, He ( $Y$ ) and metal ( $Z$ ) mass fractions, i.e.

$$\log(\dot{M}_{\text{WN}}) = -13.6 + 1.63 \log L/L_{\odot} + 2.22 \log Y$$

$$\log(\dot{M}_{\text{WC}}) = -8.3 + 0.84 \log L/L_{\odot} + 2.04 \log Y + 1.04 \log Z$$

Recent evolutionary calculations for hydrogen-poor WR stars follow mass-loss calibrations of Langer (1989) or Vanbeveren et al. (1998). Table 3 compares predictions from these calibrations with results from detailed non-LTE line blanketed spectroscopic analyses, assuming the Schaerer & Maeder (1992) mass-luminosity relationship. The formulation of Langer (1989) overestimates mass-loss rates by factors of 2–4,

while Vanbeveren et al. (1998) and especially Nugis & Lamers (2000) show much improved agreement with spectroscopic results.

*Table 3* Comparison between WR mass-loss rates, in  $10^{-5}M_{\odot}\text{yr}^{-1}$ , predicted by Langer (1989, L89), Vanbeveren et al. (1998, VDV98), semi-empirical calibration of Nugis & Lamers (2000, NL2000) with detailed non-LTE spectroscopic results (nLTE) of hydrogen poor Galactic WN and WC stars.

<i>Star</i>	<i>Sp Type</i>	<i>L89</i>	<i>VDV98</i>	<i>NL2000</i>	<i>nLTE</i>	<i>Ref</i>
WR6	WN4	12.5	5.5	5.7	3.2	a
WR147	WN8(h)	9.5	4.5	3.2	2.5	b
WR111	WC5	2.8	2.0	1.3	1.5	c
WR90	WC7	4.8	3.2	2.6	2.5	d
WR135	WC8	2.0	1.6	1.6	1.2	d

(a) Schmutz (1997); (b) Morris et al. (2000); (c) Hillier & Miller (1999); (d) Dessart et al. (2000)

The question of a  $Z$ -dependence of mass-loss in WR stars remains open. There is a clear distinction amongst spectral subtypes in galaxies of differing metal content, which has been qualitatively explained from evolutionary and spectroscopic models (Smith & Maeder 1991; Crowther 2000). LMC WN stars (Crowther & Smith 1997; Hamann & Koesterke 2000) show negligible spectroscopic difference from Galactic counterparts. The situation is less clear for the SMC, since most WR stars are complicated by binarity. Sk41 is a possible exception, whose properties compare closely with Galactic or LMC counterparts (Crowther 2000). Further progress requires detailed study of apparently single WR stars beyond the Magellanic Clouds (e.g. Smartt et al. 2000), especially in nearby metal poor galaxies such as IC10 (Massey & Armandroff 1995).

## 6. MASS-LOSS DIAGNOSTICS IN YELLOW AND RED SUPERGIANTS

Various techniques have been applied to quantify mass-loss in yellow (FG) and red (KM) supergiants, whose wind driving mechanism remains uncertain. UV/optical observations of binaries with an early-type dwarf companion permit analysis of the red-supergiant chromosphere and wind in absorption (Bennett et al. 1996). Radio continua measurements have provided upper limits to mass-loss rates of F-supergiants (Drake & Linsky 1986) and M-supergiants (e.g. Harper et al. 2001). Alternatively,

sub-mm CO emission or mid-IR dust emission permit mass-loss determinations in cool supergiants. CO emission is a reliable probe for AGB stars, although the UV radiation field from supergiant chromospheres could lead to a different CO emission per unit mass loss from star to star. Radial pulsations are generally assumed to provide the mechanism of initiating mass-loss in M supergiants, as evidenced from circumstellar dust shells (Bowers et al. 1983), with some notable exceptions – VY CMa (M5 Ia) and  $\rho$  Cas (F8 Ia<sup>+</sup>). Outflow velocities of RSG are typically 10–40 km s<sup>−1</sup> (Jura & Kleinmann 1990).

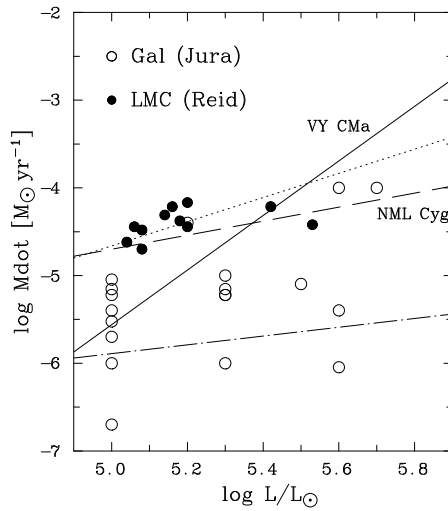


Figure 2 Mass-loss rates derived for Galactic (open circles) RSG by Jura & Kleinmann (1999) and LMC (filled circles) RSG by Reid et al. (1990) using the Jura (1986) formula, including predictions from de Jager et al. (1988, solid) and Reimers (1975, dot-dash) for  $T_{\text{eff}}=3,500\text{K}$ . Fits to Reid et al. data are by Vanbeveren et al. (1998, dashed) and Salasnich et al. (1999, dotted).

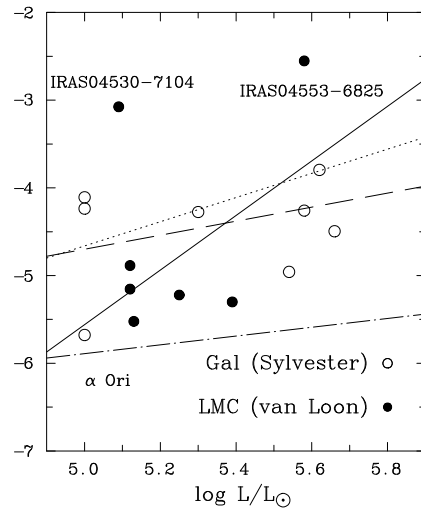


Figure 3 Mass-loss rates derived from modelling mid-IR spectroscopy of Galactic (open circles) and LMC (filled circles) RSG by Sylvester et al. (1998) and van Loon et al. (1999). Distances to Galactic RSG follow Sylvester et al. except for W Per and  $\mu$  Cep, which have been adjusted to distances derived by Garmany & Stencel (1992). Lines are as described in the adjacent caption.

Since we are concerned with massive stars in this review, we shall restrict our discussion to the most luminous ‘hypergiants’ (de Jager 1998), with  $\log (L/L_{\odot}) > 5$ . Studies have largely focussed on M supergiants, with only highly unusual FG supergiants studied in detail (e.g.  $\rho$  Cas, HR 8752, IRC+10420). The latter is widely interpreted as a RSG rapidly moving blueward (Jones et al. 1993), which has recently experienced huge variability in mass-loss rate,  $10^{-2}$  to  $10^{-4} M_{\odot} \text{ yr}^{-1}$ , via analysis of its circumstellar dust shell (Blöcker et al. 1999).

Jura & Kleinmann (1990) applied the ‘approximate’ Jura (1986) formula for intermediate mass stars to IRAS  $60\mu\text{m}$  photometry of nearby yellow and red supergiants to estimate mass-loss rates. Reid et al. (1990) followed the same approach for a sample of LMC RSG, which have been used by Vanbeveren et al. (1998) and Salasnich et al. (1999) to provide ‘empirical’ calibrations for evolutionary calculations, as illustrated in Fig. 2. Jura & Kleinmann (1990) data for Galactic RSG reveal systematically lower rates, except for VY CMa and NML Cyg. Predictions from the empirical calibration of de Jager et al. (1988, solid) and the formulation of Reimers (1975, dot-dash) are also illustrated, for an assumed  $T_{\text{eff}}=3,500\text{K}$  ( $\sim\text{M3 I}$ ). Although the scatter is large, most Galactic data lie between the Reimers (1975) and de Jager et al. (1988) calibrations.

Recently, van Loon et al. (1999) have modelled ISO spectroscopy and photometry of a similar LMC sample to Reid et al., and found rates which are 5–10 times *lower*. Meanwhile, Sylvester et al. (1998) have used the  $10\mu\text{m}$  silicate emission feature for a sample of Galactic M supergiants, following the Skinner & Whitmore (1988) relation, which was calibrated against sub-mm CO determinations. Their determinations revealed *higher* mass-loss rates than Jura & Kleinmann (1990). From this combined dataset, presented in Fig. 3, there is little evidence of a luminosity dependence of mass-loss. The Vanbeveren et al. (1998) and Salasnich et al. (1999) calibrations match Galactic data reasonably well, except for  $\alpha$  Ori (M2.2 Iab), which probably has the most secure determination. In contrast with Fig. 2, the majority of the LMC data indicate lower mass-loss rates than Galactic RSG, hinting at a metallicity dependence. However, van Loon et al. identified two LMC RSG with exceptionally high mass-loss rates of order  $10^{-3}M_{\odot}\text{yr}^{-1}$  (IRAS 04553-6825 and IRAS 04530-7104) which are unmatched in our Galaxy.

Overall, the level of consistency between different IR/sub-mm techniques remains embarrassingly poor. Sylvester et al. (1998), using the power in  $10\mu\text{m}$  silicate emission (calibrated against earlier CO line data), derived a mass-loss rate for  $\mu$  Cep (M2 Ia) which was 25 times *higher* than Jura & Kleinmann (1990) obtained from  $60\mu\text{m}$  dust emission, or 250 times *higher* than Josselin et al. (2000) based on an alternative CO line calibration of Olofsson et al. (1993). Indeed, VY CMa has values ranging over a factor of twenty –  $3.5\times 10^{-4}M_{\odot}\text{yr}^{-1}$  (Stanek et al. 1995) to  $1.6\times 10^{-5}M_{\odot}\text{yr}^{-1}$  (Josselin et al. 2000).

In summary, the mass-loss rates for RSG are by far the most controversial when recommending empirical calibrations for evolutionary calculations. The majority of mass-loss estimates lie between the Reimers (1975) and Vanbeveren et al. (1998) calibrations. This is illustrated in Table 4, where we compare rates assumed in the recent evolutionary

model of Meynet & Maeder (2000) for an initially rapidly rotating  $40M_{\odot}$  star with ‘empirical’ calibrations of Kudritzki & Puls (2000) for OBA stars, Vanbeveren et al. (1998) for RSG and Nugis & Lamers (2000) for WR stars. Agreement is very good, except for the brief, low mass-loss B supergiant phase and *highly uncertain* high mass-loss RSG phase. Continuing studies into the latter are highly desirable. Typical outflow velocities for each evolutionary phase are also indicated in Table 4.

*Table 4* Summary of wind properties during various phases during the evolution of a rotating  $\sim 40M_{\odot}$  star ( $V_{\text{init}} = 300 \text{ km s}^{-1}$ ) at solar metallicity (following Meynet & Maeder 2000). Two sets of mass-loss rates are given - those adopted by Meynet & Maeder,  $\dot{M}^{\text{MM}}$ , and those taken from recent empirical calibrations,  $\dot{M}^{\text{emp}}$ .

<i>Age</i> <i>Myr</i>	<i>Mass</i> $M_{\odot}$	$\log L$ $L_{\odot}$	<i>Sp Type</i>	$\dot{M}^{\text{MM}}$ $10^{-6} M_{\odot} \text{ yr}^{-1}$	$\dot{M}^{\text{emp}}$ $10^{-6} M_{\odot} \text{ yr}^{-1}$	$v_{\infty}$ $\text{km s}^{-1}$
0.0	40	5.4	O4 V	1.2 <sup>a</sup>	0.4 <sup>e</sup>	3000 <sup>h</sup>
3.7	35	5.5	O7 I	2.1 <sup>a</sup>	2.1 <sup>e</sup>	2100 <sup>h</sup>
5.1	31	5.7	B3 I	7.6 <sup>a</sup>	0.7 <sup>e</sup>	490 <sup>i</sup>
5.1	31	5.8	A0 I	22. <sup>b</sup>	14. <sup>e</sup>	170 <sup>i</sup>
5.1	29	5.8	M0 I	400. <sup>b</sup>	86. <sup>f</sup>	30 <sup>j</sup>
5.3	18	5.7	WNL	30. <sup>c</sup>	26. <sup>g</sup>	750 <sup>h</sup>
5.3	16	5.6	WNE	25. <sup>d</sup>	31. <sup>g</sup>	2000 <sup>h</sup>
5.4	13	5.5	WCE	15. <sup>d</sup>	28. <sup>g</sup>	2500 <sup>h</sup>

(a) Lamers & Cassinelli (1996); (b) de Jager et al. (1988); (c) Nugis et al. (1988); (d) Langer (1989) corrected for clumping (Schmutz 1997); (e) Kudritzki & Puls (2000); (f) Vanbeveren et al. (1998); (g) Nugis & Lamers (2000); (h) Prinja et al. (1990); (i) Lamers et al. (1995); (j) Jura & Kleinmann (1990)

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